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MEMORANDUM FOR PR (In-House Publication)

FROM: PROI (TI) (STINFO)

30 November 1999

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-1999-0226**
Talley, D., "Basic Research in Supercritical Combustion" (BFI)

49th JANNAF Propulsion Meeting (Tucson, AZ, 14-16 Dec 1999)

(Statement A)

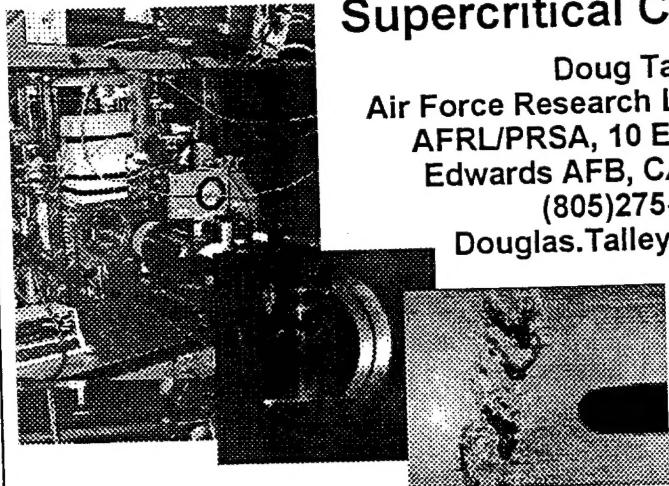


BRIEFING FOR INDUSTRY

16 Dec 1999



Basic Research in Supercritical Combustion



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6.1 Objectives

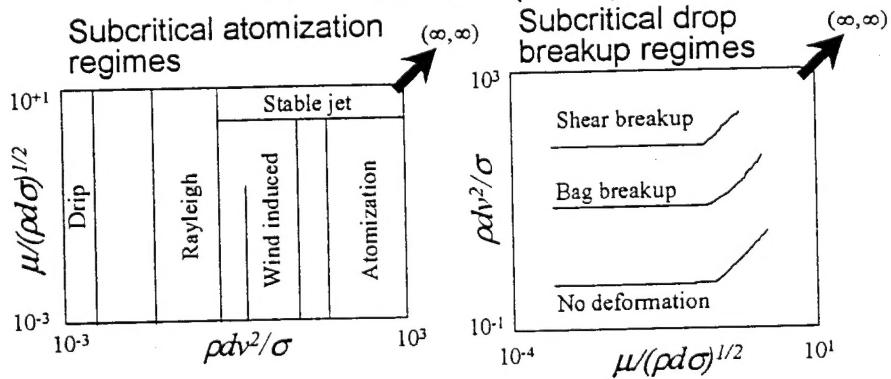
- Determine the mechanisms which control the breakup, transport, mixing, and combustion of sub- and super-critical droplets, jets, and sprays.

	Prior	FY99	FY00	FY01
6.1 Funding (\$1,000's)	1318	150	141	141

The Problem

- It is often advantageous to operate combustion chambers at pressures exceeding the critical pressure of one or both propellants.
 - Higher chamber pressures lead to greater performance (Isp).
- At supercritical pressures, the distinct difference between gas and liquid phases disappears.
 - Conventional "spray combustion" experience no longer applies.
- It is not known how to replace conventional "spray combustion" models in engine design codes.
 - *The lack of understanding leads to potentially large engine design errors.*

The Problem (con't)



Surface tension σ vanishes at supercritical conditions. Conventional atomization and breakup parameters become *infinite*, where no data exists.

Supercritical atomization and breakup regimes are unknown.

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The Problem (con't)

- Supercritical combustion is complicated by several factors not present in subcritical combustion:
 - Vanishing surface tension.
 - Equivalent gas and liquid phase densities.
 - Strongly enhanced gas / liquid solubility.
 - Different reaction kinetics.
 - Mixing induced critical point variations.
 - Property computation / singular behavior.
 - Zero enthalpy of vaporization.
 - Infinite specific heat (C_p).
 - Infinite compressibility.
- *Deeply fundamental questions such as whether droplets can even exist were hotly debated when this work began.*

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Technical Approach

- Windowed pressure vessel operating at supercritical pressures.
- Cryogenic fluid capability (LOX, LN2)
- Capability to produce supercritical droplets and jets.
- Shadowgraph, Schlieren, and Raman visualization of concentration fields.
- Capability to drive flows with an acoustic driver

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Payoffs

Provide alternatives to trial and error development

- Performance: Injector related design uncertainties translate to 3-6 sec Isp on a booster class LOX/H₂ engine.
 - ◆ Comparison: IHPRT 2010 Isp objective is 13.5 sec.
 - ◆ 3-6 sec Isp buys 1.6 - 3.3 tons payload on the Space Shuttle Main Engine (SSME) worth \$20-40M per launch.
- Operability and Lifetime: Injector related performance deficit required SSME turbopumps to be run at 105% rated power, increasing pump stress.
 - ◆ Pumps are the most expensive SSME maintenance item.
 - ◆ Turb. blade cracking problem is also probably inj. related.
- Instability: Injector related Saturn F-1 instability problem required over 800 full scale tests to solve.
 - ◆ Present day costs: over \$750K per test. Total: \$600 million.

Trial-and-error approaches risk significant cost overruns
that can no longer be afforded

OK
150
← Public
release
info?

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FY99 Accomplishments

For subcritical and supercritical mixing layers:

- Measured the growth rate for a wide variety of propellant combinations
- Developed comprehensive model to predict mixing layer growth rates over four orders of magnitude in density ratio
- Performed fractal analysis of mixing layer geometry
- Installed and performed initial Raman measurements of species distributions.

Evolution of Mixing Layers in Transition from a Subcritical to a Supercritical State

Acknowledgements:

Bruce Chehroudi

Rich Cohn

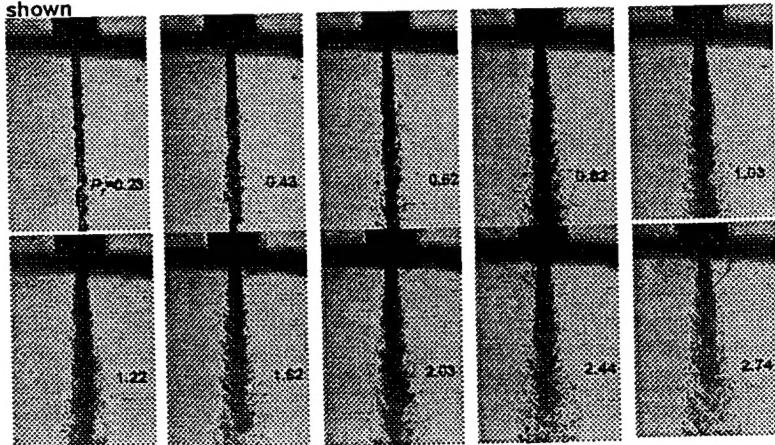
Roger Woodward

Ed Coy



N_2 into N_2

Back-illuminated images. Chamber is at a fixed supercritical temperature of 300 K but varying sub- to supercritical pressures ($P_{critical} = 3.39$ MPa). $Re = 25,000$ to $75,000$. Injection velocity: 10-15 m/s. Froud number = 40,000 to 110,000. Injectant temperature = 99 to 120 K. Reduced pressures are shown

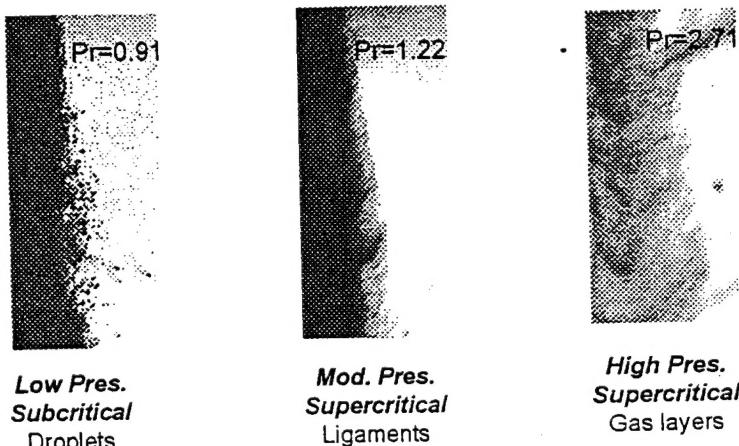




PRESSURE DEPENDENT MIXING LAYER STRUCTURE

Nitrogen/nitrogen system ($P_{cr} = 3.39 \text{ MPa}$, $T_{cr} = 126 \text{ K}$)

$T_{inj} = 128 \text{ K}$, $T_{amb} = 300 \text{ K}$, mass flow = 350 mg/s



Low Pres.
Subcritical
Droplets

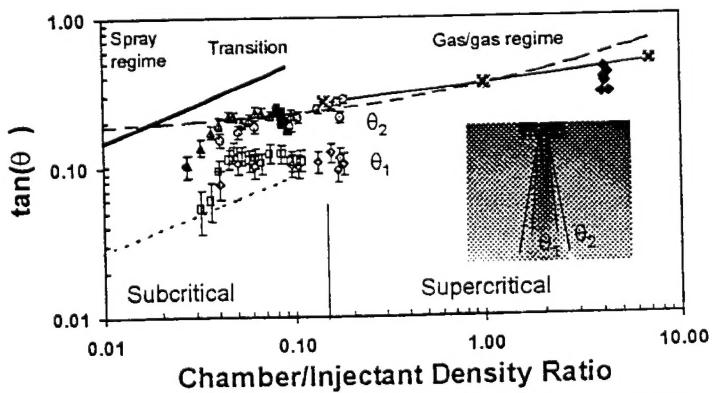
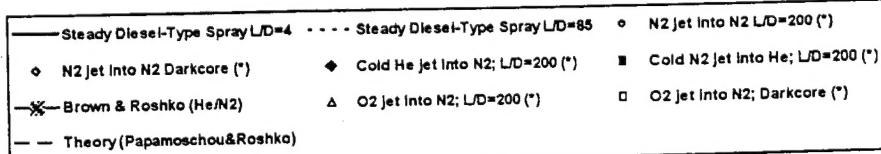
Mod. Pres.
Supercritical
Ligaments

High Pres.
Supercritical
Gas layers

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Sub- and Super-critical Mixing Layer Physics

Chehroudi et. al., AIAA 99-0206, AIAA 99-2489



Characteristic Times

- Characteristic bulge formation time (τ_b) at the jet interface (Tseng et al.): $(\rho_l L^3/\sigma)^{1/2}$; ρ_l , L , σ are liquid density, characteristic dimension of turbulent eddy, and surface tension, respectively.
- Characteristic time for gasification (τ_g) (D-square law): D^2/K ; D and K are drop diameter and vaporization constant.
- A Hypothesis: If these two characteristic times (calculated for appropriate length scales) are comparable then an interface bulge may not be separated as an unattached entity (onset of the gas-jet behavior at supercritical condition)

Similar equation format for different cases

- Theoretical isothermal liquid spray growth rate (θ_s) based on Orr-Sommerfeld equation and stability analysis to find the wavelength of the most unstable interface wave:
$$\theta_s \equiv 0.27 [0 + (\rho_g/\rho_l)^{0.5}]$$
- Papamoschou/Rashko theory for incompressible variable-density gaseous mixing layer/jet:
$$\theta_{P/R} \equiv 0.17 [1 + (\rho_g/\rho_l)^{0.5}]$$
- Dimotakis theory for incompressible variable-density gaseous mixing layer/jet:
$$\theta_D \equiv 0.212 [0.59 + (\rho_g/\rho_l)^{0.5}]$$
- ALL HAVE THE SQUARE ROOT OF DENSITY RATIO AND THE SAME EQUATION FORMAT

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Correlation

- Based on the information of the previous slide the following "intuitive/smart" equation is proposed for both sub- and supercritical measured growth rates:

$$\theta_{ch} \equiv 0.27 [(\tau_b / (\tau_b + \tau_g)) + (\rho_g / \rho_l)^{0.5}]$$

Note:

- For isothermal liquid case: $\tau_g \gg \tau_b$ and $\tau_g \rightarrow \infty$. It then collapses to the isothermal spray case.
- For subcritical the $(\tau_b / (\tau_b + \tau_g))$ is calculated until it reaches 0.5. After that it is maintained constant at 0.5 for supercritical gas-like jet. The transition point is found to be approximately when $(\tau_b / (\tau_b + \tau_g)) \equiv 0.5$ (i.e. $\tau_b \equiv \tau_g$).

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Correlation (con't)

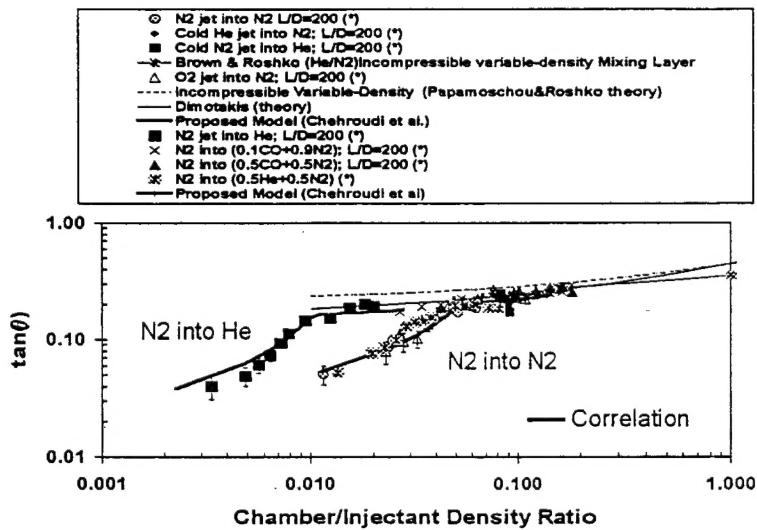
- $(\tau_b / (\tau_b + \tau_g))$ is assumed to be a dominant function of the density ratio (ρ_g / ρ_l) ; i.e. $\tau_b / (\tau_b + \tau_g) = F(\rho_g / \rho_l)$.
- The function F is only calculated for the N2-into-N2 case and is taken to be the same for other (N₂-into-He and N₂-into-Ar) cases. That is, for example, for N₂-into-He:

$$\theta_{ch} \equiv 0.27 [G(\rho_g / \rho_l) + (\rho_g / \rho_l)^{0.5}] \text{ where } G(\rho_R) = F(\rho_R)$$

$$\rho_R = (\rho_g / \rho_l); \quad \rho_R' = \rho_R - (1-X)\rho_R = X\rho_R$$

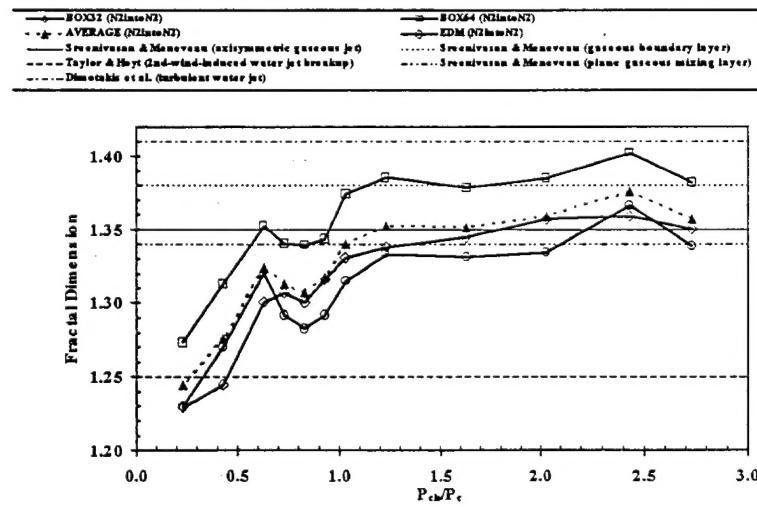
$$X=1.0 \text{ for N}_2\text{-into-N}_2; \quad X=0.2 \text{ for N}_2\text{-into-He}; \quad X=1.2 \text{ for N}_2\text{-into-Ar.}$$

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Empirical Correlation Results



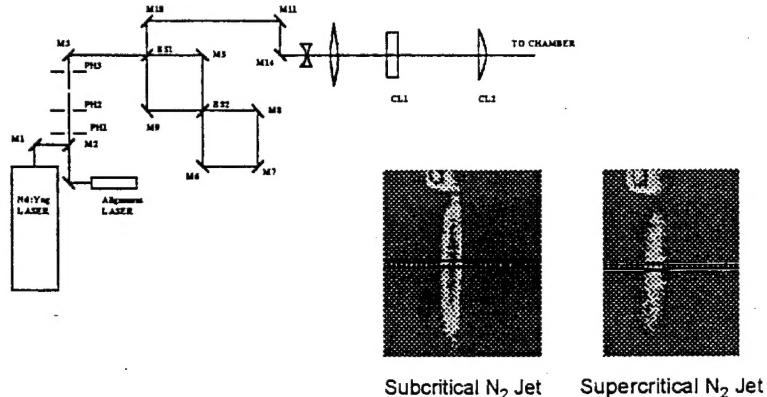
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Fractal Dimension vs Reduced Pressure

Chehroudi et. al., AIAA 99-2489



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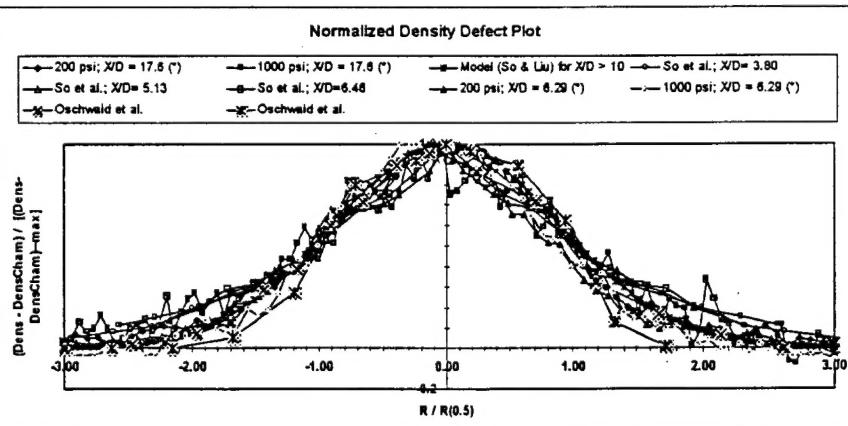
Raman Imaging Set-up



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Preliminary Raman Results

- Plot contains a theoretical model, supercritical jets from AFRL and DLR, and gas jets
- Self-similarity behavior is observed



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Planned for FY00

- Complete Raman species measurements; reduce and analyze data.
- Install acoustic drivers and investigate the effect of acoustic waves.

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Summary and Conclusions

- Structural differences in cryogenic jets have been observed below and above the thermodynamic critical point.
- Liquid-Jet like appearance occurs up to near the critical point, similar to second wind-induced liquid jet breakup regime.
- Gas-jet like appearance occurs above the critical point. No drops are observed.
 - Supercritical spreading rate measurements agree quantitatively with incompressible variable density mixing layer experiments and theory.
 - Supercritical fractal dimensions agree quantitatively with gas jet measurements.
- New and existing mixing layer growth rate experiments and theory have for the first time been consolidated into a single plot as a function of density ratio, where the density ratio spans three orders of magnitude.
- A physical mechanism and correlation have been proposed to describe the transition from spray to gas jet behavior.

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Summary and Conclusions (con't)

- Preliminary analysis of Raman data indicates self-similar spreading behavior much like a gas jet.